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Application of GPS heights to Bay of Fundy multibeam data

David W. Dodd

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Executive Summary

Between 1996 and 2009 several different vessels conducted mutibeam surveys in the Bay of Fundy. Removal of the tidal effect and the establishment of a vertical reference were the most challenging aspects of the data reduction process. Due to the tidal range (8 to 16 metres) these effects must be removed in order for the results to be used effectively. Simply establishing gauges and measuring tides is extremely challenging, which makes this environment ideal for the use of GPS heights. Surveys conducted in 2007, 2008 and 2009 observed GPS heights during multibeam data collection. Surveys conducted prior to 2007 relied on a combination of tide gauge observations and predicted tides. The mandate for this project was to reduce the 2007 to 2009 surveys to a common Mean Sea Level (MSL) datum, and to try to incorporate surveys conducted prior to 2007.

GPS heights from multibeam surveys conducted by the Creed, Matthew, Plover and Pipit in 2007, 2008 and 2009 were used to remove tidal effects and establish the vertical datum. GPS height observations were evaluated with respect to the Saint John tide gauge. GPS Tides were edited to remove sections where high-accuracy GPS solution was not available. Depths were determined relative to the International Terrestrial Reference Frame (ITRF), as established by the GPS observations. Lines where GPS heights were not available were removed from the process. Depths from each survey were used to create regular gridded surfaces at a 5X5 metre resolution. All surfaces were compared to ensure consistency in overlap areas and combined into a single surface.

Three surveys conducted by the Creed prior to 2007 (without GPS heights) were included in the final surface. These included surveys conducted in 1996, 1999 and 2006. Initial tidal references were derived from predicted tides. Surfaces derived from these tidal datums were adjusted to the ITRF97 (1997 epoch) reference through a geoid-to-ellipsoid model (Canadian Spatial Reference System [CSRS] NT2). These surfaces were then compared to 2007-2009 surfaces where overlap occurred. Biases between the GPS derived ITRF surfaces and the MSL shifted surfaces ranged between 0.15 to 0.45 m. Sea Surface topography was not included in the shifting and will be included in the bias value. The standard deviation (1σ) ranged between 0.6 and 1.6 metres. The high standard deviations can be attributed to the tidal model (Scotia Shelf) used to derive the predicted tides. Surveys conducted by the UNB OMG using the Heron were also incorporated into the final project.

Acknowledgements

The following people and/or groups were instrumental in the completion of this project

- CARIS provided the use of HIPS and Bathymetry Editor software
- Ian Church of the University of New Brunswick's Ocean Mapping Group (OMG) for creating the predicted tide files
- Doug Cartwright of OMG for providing the raw multibeam data, some processed data and facilitation of data exchange
- Phillip MacAulay of Canadian Hydrographic Service (CHS) Atlantic for providing Saint John tide gauge data
- Jonathan Griffin of CHS Atlantic for providing the CARIS HDCS multibeam and GPS data
- Russell Parrott of Geological Survey of Canada (GSC) Atlantic for providing funding

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Application of GPS Heights to

Bay of Fundy Multibeam Data

Changes Summary

Date (yyyy-mm-dd)	User	Version	Summary of Changes
2010-02-18	Dodd	20100218	Created Document
2010-03-29	Dodd	20100218	First Draft Completed
2010-03-30	Dodd	20100329	Preliminary report
2010-03-31	Dodd	20100331	Final
2010-04-05	Dodd	20100405	Completed recommendations from previous version (20100331)
2010-04-16	Dodd	V2 20100416	Started version 2 enhancements: • Creed VCF • Heron 2007, 2008, 2009 • XYZ map sheet export • WebTide vrs GPS Tide evaluation
2010-05-03	Dodd	V2 20100503	Completed enhancements
2010-05-04	Dodd	V2 20100504	Added comments from Russell Parrott and Jonathan Griffin

1 Introduction

Many groups involved in hydrographic surveying and ocean mapping are using High-accuracy GPS for three dimensional positioning. Of particular interest to hydrographers is the vertical component. The benefit of this form of vertical positioning is that objects in question (sea surface, water column, sea floor etc) are referenced directly to a mathematically derived reference ellipsoid.

Hydrographic surveying has traditionally been conducted solely for the purpose of creating nautical charts for safety of navigation. It now encompasses a multitude of methods and applications in the marine environment, and has a vital role in coastal zone management. The coastal zone encompasses a wide swath along the shoreline that includes both the land and sea, and properly merging information from the two is essential for the analysis of coastal processes and sound management decisions. In the past, vertical land (topography) and ocean (bathymetry) data were collected for different purposes, using different methods and related to different vertical reference surfaces. The need to merge the two data types has driven the need to resolve these differences.

One surface that is used for modern data collection on both land and sea is a reference ellipsoid. Traditionally, reference ellipsoids were used to define horizontal datums. With the emergence of high-accuracy GPS, reference ellipsoids are being used to define vertical datums. Data collected both on land and at sea can be related to the same satellite based vertical reference surface, making the merging of the two a trivial process. Although these reference ellipsoids are convenient, they are not physical surfaces, such as those defined by gravity (geodetic datum) or mean sea level (tidal datum); therefore, for analysis and map/chart production, GPS derived vertical information must be translated. Translations from the ellipsoid to geodetic or tidal datums are usually performed through transformation models. The ellipsoid can be used as the reference for all of the translation models.

Chapter 2 of this report presents some background material that outlines the major components of surveying with respect to the ellipsoid. Chapter 3 summarizes the project and data and Chapter 4 outlines the basic procedures used. Chapter 5 looks at vessel configuration with particular emphasis on the Creed. Chapter 6 looks at a comparison of GPS tides derived surfaces and Webtide derived surfaces. Chapter 7 presents the results and Chapter 8 discusses the deliverables. The final chapter presents conclusions and recommendations.

2 Background

In order to understand the issues surrounding surveying to the ellipsoid it is necessary to understand the various contributors to the process. The following sections briefly describe:

1. Vertical components
2. Ellipsoidal, geoidal and tidal vertical datums
3. Sea surface topography
4. Hydrodynamic models
5. High-accuracy GPS

2.1 Vertical Components

The following list describes the terminology associated with the vertical components of hydrographic surveying with respect to the ellipsoid (see Figure 1).

- Observed GPS height is the distance from the Ellipsoid to receiving antenna phase centre
- ΔZ (antenna) is the vertical offset between the antenna phase centre and the vessel reference point (RP).
- ΔZ (transducer) is the vertical offset between the RP and transducer.
- Observed depth is from transducer to bottom.
- Dynamic draft (DD), or settlement and squat, is the change in the vessel's vertical position in the water due to speed through the water (water surface to RP).
- Heave is the short term vertical movement of the vessel with the water surface (WS), about a mean water level (MWL), measured at the RP.
- Removal of heave, settlement and squat produces a water level (WL), which includes the tidal component.
- Removal of the tidal component from the WL produces the Chart Datum.
- Ellipsoid to Chart Datum is the separation model (SEP)

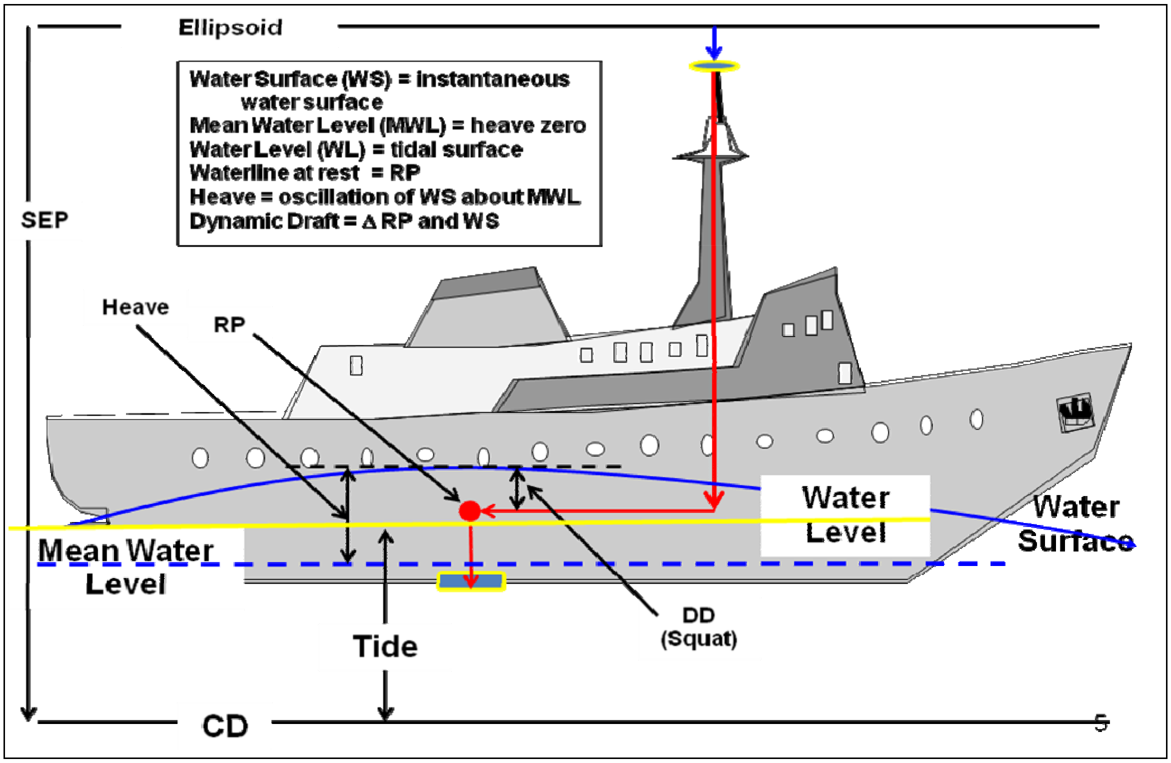

Figure 1: Vertical Components

2.2 Vertical Datums

Vertical reference surfaces can be categorized under three general headings; tidal, geodetic (both physical surfaces) and ellipsoidal (mathematical surface). Traditionally, bathymetric data has been collected and stored relative to a tidal datum and topographic data relative to a geodetic datum.

Bathymetric data displayed on charts are referenced to a low water tidally referenced vertical datum below which the water surface will not usually fall (e.g. Lowest Astronomical Tide [LAT], Mean Lower Low Water [MLLW]). Topographic data, on the other hand, are often referenced to a local geodetic datum, approximated by Mean Sea Level (MSL), which is above LAT and MLLW. A geodetic datum is a surface that varies with gravity (geoid). MSL is a surface that varies from the geoid due to sea surface topography (see section 2.3). The chart datum surface varies from MSL due to the effects of tides and ocean dynamics.

GPS derived heights must be transformed from the reference ellipsoid to the geoid or chart datum. In some cases, data sets can be adjusted by simply applying a constant offset. In other cases it is necessary to apply more complex algorithms taking into account sea surface topography and hydrodynamic ocean models.

2.2.1 Geodetic Vertical Datum

When the height of an object is expressed, it must be related to something. The height of a ceiling is relative to the floor. The height of a building is relative to the ground outside. The elevation of a mountain is relative to Mean Sea Level (MSL). The expression MSL, when applied to elevation, usually refers to the height above the local geodetic datum. The Canadian Geodetic Vertical Datum (CGVD28) and the USA North American Vertical Datum (NAVD88) are referenced to MSL at Rimouski, Quebec. The elevations of all reference marks (bench marks) within the two systems are related to MSL at Rimouski through precise levelling and gravity observations. These geodetic vertical reference datums do not coincide with observed MSL at any other location due to atmospheric and oceanographic effects. These reference surfaces do, however, coincide with the geoid.

The geoid is a surface of equal gravity potential and is used to approximate the shape of the earth. The geoid coincides approximately with MSL and is represented by a geodetic vertical reference datum, as discussed above. If there were no long term atmospheric or oceanographic effects (e.g. prevailing winds and currents), then MSL determined over a long period (~19 years) would coincide with geoid. In reality, determination of MSL at a location will vary from the geoid by up to ±1 metre. This variation is known as sea surface (or ocean) topography.

2.2.2 Chart Datum (CD)

Chart datums (CD) are used on nautical charts to reference water depths. Traditionally, bathymetric data has been collected relative to a survey (or sounding) datum, then translated to chart datum for storage and chart production. As a result, most legacy bathymetric data contains depths relative to some local chart datum.

The following is a listing of some chart datum definitions:

- MLW Mean Low Water
- MLLWLT Mean Lower Low Water Large Tide
- MLLW Mean Lower Low Water
- LNT Lowest Normal Tide
- LLWLT Lower Low Water Large Tide
- LAT Lowest Astronomic Tide (atmospheric and oceanographic effects removed)

Chart datums are only fully valid at the location where the tides are observed. Even if MSL is the same at two locations (relative to the geoid), the low water datum will likely be different. One of the most significant challenges in traditional hydrography is establishing the relationship between the instantaneous water surface and chart datum, away from tide gauge locations. Tidal correctors are measured at tide gauge locations and then translated to the survey site through co-tidal charts or tide zoning. Uncertainty in the relationship between the instantaneous water surface and CD at the survey site is a significant component of the overall depth uncertainty.

The separation between chart datum and the geodetic vertical datum can be divided into two parts; CD to MSL and MSL to geoid. CD to MSL is established through hydrodynamic modeling. MSL to geoid is established through Sea Surface Topography (SST) modeling.

2.2.3 Reference Ellipsoid

The shape of the geoid can be approximated by a three-dimensional ellipse (ellipsoid). Because the earth is symmetric about the poles, the ellipsoid can be defined with a bi-axial ellipse, with the semi-minor axis aligned with the earth's axis of rotation and the semi-major axis aligned with the equatorial plane. This mathematical representation of the earth allows for relatively simple geographic (latitude, longitude and height) position computations. The vertical relationship between the ellipsiod, geoid and terrain is:

$$h = H + N$$

Where:

h = ellipsoid height
H = orthometric height
N = geoid height, also known as the geoid/ellipsoid undulation

The reference ellipsoid does not define a datum, it simply defines the parameters of the ellipse. A combination of the ellipsoid and its location with respect to the earth, defines a datum. The GRS80 ellipsoid is used in the definition of both the NAD83 and WGS84 datums.

GPS heights are determined relative to the mathematically defined ellipsoid. These heights must be translated to the geoid, through a geoid height model, in order to give them a physical relationship to the earth. Geoid models are determined through co-located GPS and gravity observations. These geoid/ellipsoid separation models can be established using land based techniques including GPS observations, levelling and gravity observations. They can also be established using space based techniques with specifically designed and tasked gravimetric satellites. Some existing models are GEOID96, 99, 03, and 08, and EGM96 and 08.

As more information is being collected relative to a reference ellipsoid through GPS observations, that ellipsoid is becoming more popular as the reference surface for all information. This mathematical surface should not change. Translation to and from the geoid and chart datums can be accomplished through surface models. As the relationships between the different surfaces changes or becomes better established, the models can be updated without affecting the base data.

Figure 2 depicts the relationship between chart datum (CD), the geoid and the ellipsoid. The ellipsoid is depicted as the primary reference (horizontal line) and all other surfaces are shown with respect to it. "SEP" refers to the CD to ellipsoid separation at tide gauge locations, which are depicted as tide staffs in the figure. The geoid is shown as a straight sloping line; again, with respect to the ellipsoid. MSL and MLW are shown as undulating lines with similar but different trends. This is meant to indicate that they are closely related, but their separation will differ from place to place. This difference is represented by the hydrodynamic model. The separation between the geoid and MSL is shown as sea surface topography (SST).

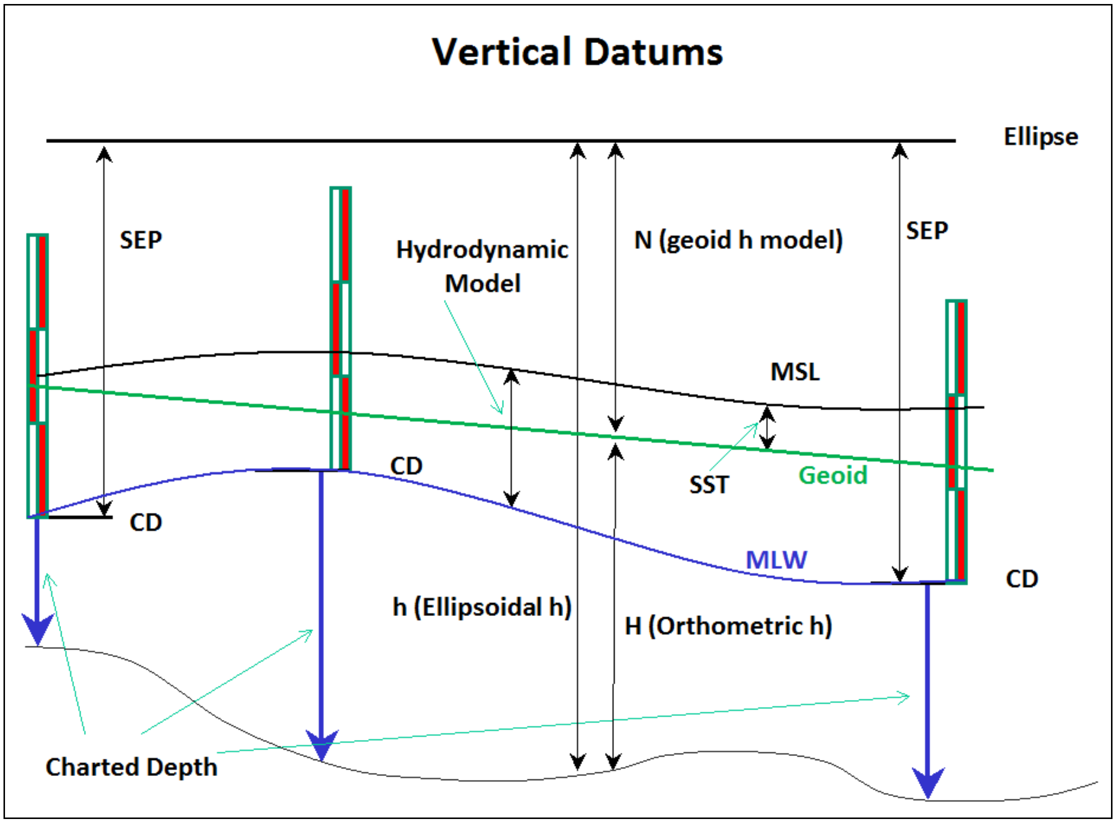

Figure 2: Chart datum, geoid, ellipsoid relationships

2.3 Sea Surface Topography

Sea Surface Topography (SST) is the average deviation of the surface of the ocean with respect to the geoid. This deviation is caused by atmospheric effects such as prevailing winds and weather patterns, as well as oceanographic effects, such as ocean currents. For example, the centre of the Gulf Steam is approximately 0.5 metres higher, relative to the geoid, than the east coast of North America. Figure 3 displays a colour shaded map of sea surface topography on the world's oceans.

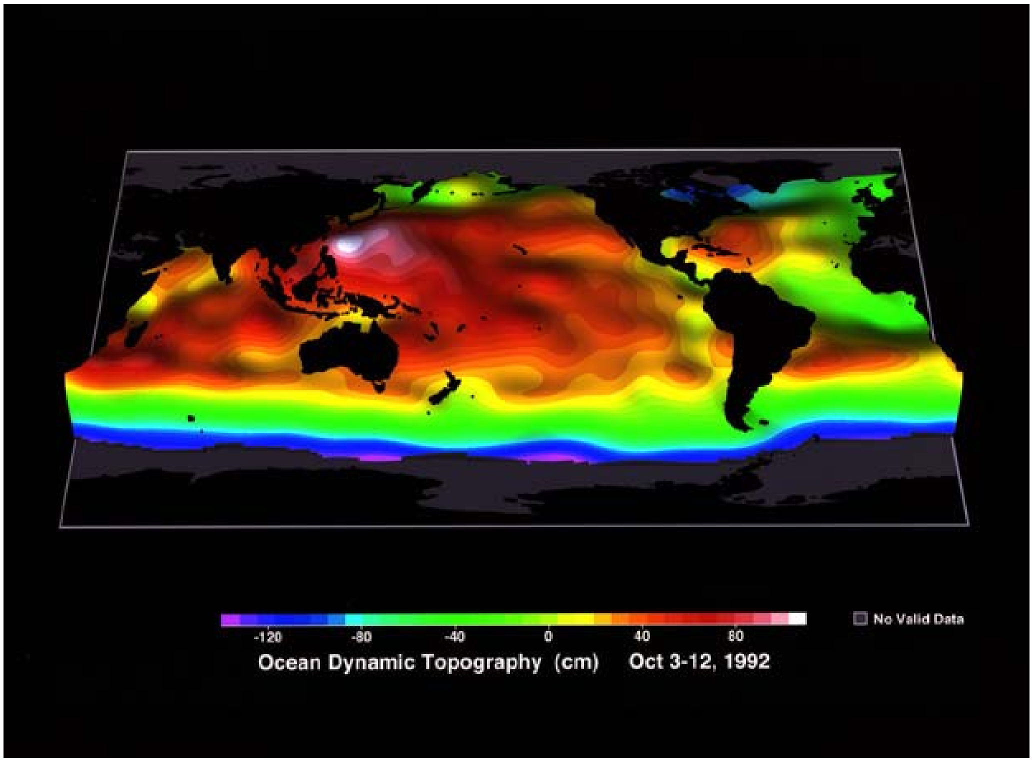

Figure 3: Map of Sea Surface Topography. [Taken from NASA, 2009]

Sea surface topography can be determined at tide gauges where the MSL has been observed, and the geodetic datum tied in through levelling. Alternatively, the geoid can be established relative to the reference ellipsoid through the geoid model, which requires establishment of the ellipsoid height at the tide gauge through GPS observations. Sea surface topography in the offshore is measured using satellite altimetry.

2.4 Hydrodynamic Models

Hydrodynamic models are derived from sophisticated applications used to estimate water level. Water level can be estimated for a given date and time for tidal predictions, or for a given mean tidal surface such as MLLW with respect to MSL. It is the latter that is used to translate data between MSL and CD.

Hydrodynamic models describe the reaction of a water body given certain boundary conditions and driving forces. The boundary conditions are coastlines and bathymetry. The driving forces are astronomic (sun/moon system) and oceanographic (currents etc.). Surfaces are derived by simulating the reaction of a body of water when it is forced over the given bathymetry and up against the coastline. The reaction of the water body is predicted using a set of algorithms based on fluid dynamics derived from Newton's laws of motion. In some models the solution is constrained by known tide station parameters.

2.5 GPS Positioning

High-accuracy GPS for vertical positioning is relatively new to the hydrographic community. In the past, the vertical relationship between the GPS antenna and the transducer was important, but not vital. Now, with the use of GPS vertical positioning to establish bathymetry, it is essential that all aspects related to the measurement of that position be understood and dealt with appropriately. All measurement uncertainty will propagate directly into the final depth. Total uncertainty resulting from the use of GPS heights includes; the uncertainty in the GPS vertical position of the antenna phase center, the measurement of the three dimensional offsets between the phase center and transducer, and the translation of the vertical position to the transducer (or reference point), taking into account the effects of pitch and roll.

High-accuracy GPS in hydrographic surveying has two basic applications; bathymetric data collection and chart datum development. For bathymetric data collection, GPS observations at the antenna are related directly to the depth observations through vessel offset measurements, thus providing a direct measurement from the ellipsoid to the sea floor. All vertical movement of the vessel, including tides, heave, static and dynamic draft are included in the GPS height observation. Chart datums can be established from GPS tide buoys to estimate the mean water surface, relative to the ellipsoid. This datum is used to translate the ellipsoid related bathymetric data to chart datum.

Figure 4 shows the relationship between the reference ellipsoid, a tide gauge buoy and vessel, and chart datum. The buoy height, combined with its draft observation, provides the water surface measurements for datum determination in relation to a shore-based tide gauge. The datum-to-ellipsoid relationship is represented by a separation (SEP) model. The vessel GPS height is connected to the depth observation through the “Z” offset. Although this offset is shown here as a single value, it actually varies with the pitch and roll of the vessel. The vessel air draft (antenna to waterline), taking into account all vessel motion, including heave, pitch, roll, long term draft and dynamic draft, can be used to validate water level observations and datum determinations.

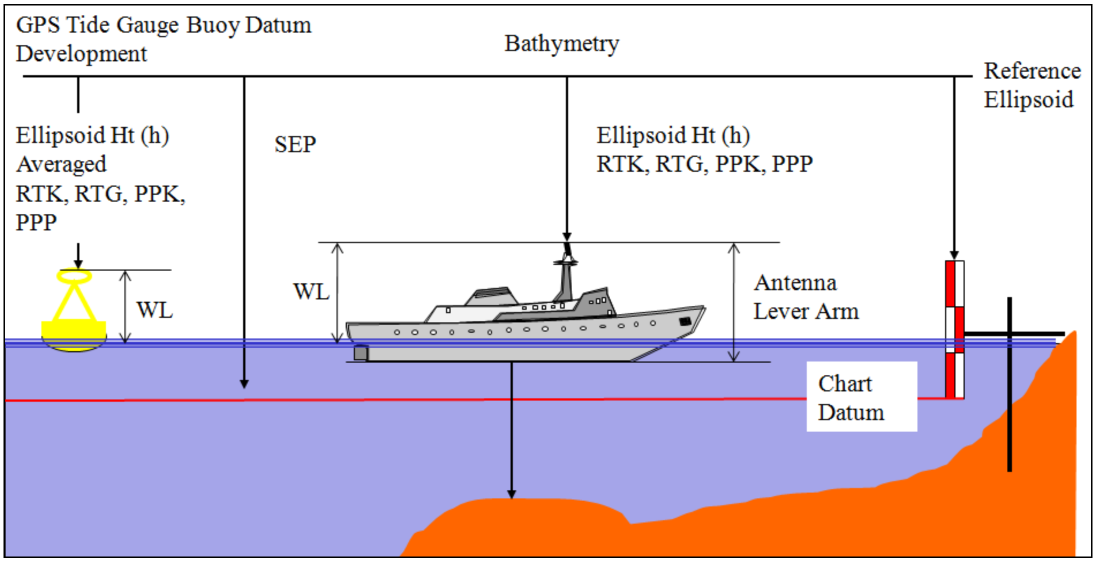

Figure 4: Relationship between reference ellipsoid, antenna, water line (WL) and chart datum.

Tide gauge buoys can be used to establish a chart datum in the area of the survey. Ideally, a water level transfer from a tide gauge in the area, with an established datum, is used to determine the datum at the buoy. Only long period buoy movement caused by the tides is required; therefore, the short term movement, such as heave, can be filtered out through averaging. A critical component for the establishment of a datum using a GPS tide buoy, is the waterline determination (distance from antenna to water line). Any error in the measurement of this offset will translate directly into the datum.

Tide gauge buoys can also be used to validate and strengthen hydrodynamic models by providing water level observations away from the shore. Carefully calibrated and positioned (with respect to the ellipsoid) bottom mounted gauges can be used in lieu of the GPS buoy.

Ship borne bathymetric data collection systems measure depths relative to a transducer. These depths are then translated to the vessel reference point. The GPS height, determined at the antenna, is also translated to the vessel reference point. Combining the GPS height and water depth provides a direct measurement from the ellipsoid to the sea floor. The change in vertical separation between the antenna and vessel reference point will vary depending on the horizontal and vertical offsets (as measured in the vessel frame), and the degree of vessel pitch and roll. Figure 5 shows an example of the effect of pitch on the vertical offset between the antenna and vessel reference point (RP), given a horizontal offset of “*y*”. The “at-rest” vertical separation, with no pitch, is represented by “*z*”, the vertical separation with a pitch value is represented as the red dashed line (*z’*). Without a horizontal offset, the change in vertical separation is minimal and the ”*z*” lever arm is always shorter.

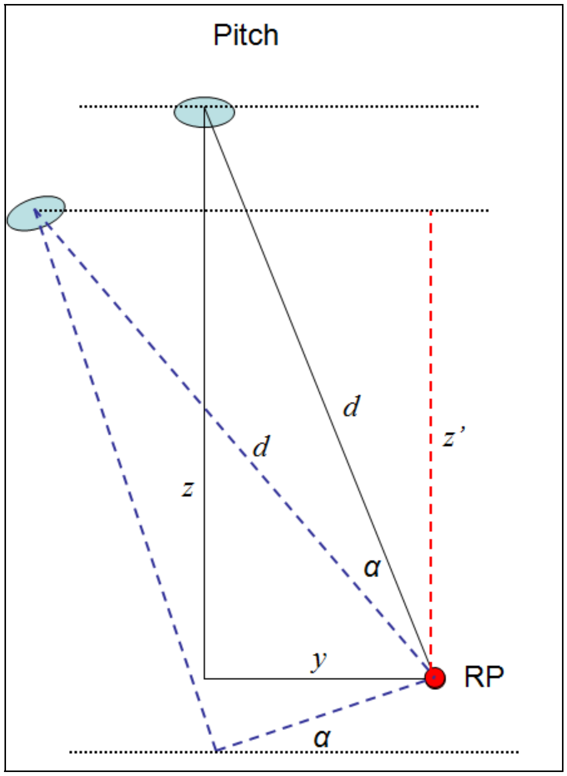

Figure 5: Effect of vessel pitch on height translation to the vessel reference point

3 Project and Data

The primary focus of this project is the establishment of a common datum for a series of multibeam surveys conducted in the Bay of Fundy between 1996 and 2009. Much of the multibeam data were received in the form of CARIS HDCS files from the CHS Atlantic region. GPS position observations were also received from CHS Atlantic. Tide gauge observations for Saint John (Gauge 65) were obtained from the CHS Atlantic at the Bedford Institute of Oceanography (BIO). Raw multibeam observation data were obtained for the UNB Ocean Mapping Group (OMG). Predicted tide observations (MSL) were obtained from the OMG using the BIO "WebTide" program using the Scotia Shelf model.

Tide gauge and GPS height comparisons were conducted using specifically developed MatLab routines. The multibeam data were reprocessed using CARIS HIPS version 7.0, where 5X5 metre surfaces, relative to the ITRF ellipsoid, were created. Surface comparisons, translations and combinations were performed in CARIS Bathymetric Editor version 2.3. The translation values between the CSRS geoid and ITRF (N) were determined using the CSRS program GPS-H version 2.1

The following is a table of surveys and years:

Vessel	Year	Area
Creed	1996	Chignecto
Creed	1999	Central BoF
Creed	2006	Western BoF and Grand Manan
Creed	2007	SJ to Gr Manan
Matthew	2007	Bay of Fundy
Pipit	2007	Bay of Fundy
Plover	2007	Bay of Fundy
Creed	2008	Bay of Fundy
Matthew	2008	Bay of Fundy
Pipit	2008	Bay of Fundy
Plover	2008	Bay of Fundy
Matthew	2009	Bay of Fundy
Plover	2009	Bay of Fundy
Heron	2009	Saint John Harbour

4 Methodology

1. Gather Data

    - MB (HDCS)
    - GPS hts (OMNIStar)
    - Tide Gauge (Saint John – 065)
    - Vessel Configuration
    - Vessel diagram showing location of transducer, antenna, RP and MRU

2. Evaluate offsets

    - Find time when vessel near to Saint John Tide Gaugeand in SJ
    - Develop vertical offset diagram showing (See Figure 6)
        - ITRF ellipsoid
        - Chart Datum
        - waterline
        - Tide Gauge
        - Vessel Antenna, Transducer

    - Update VCF inserting Navigation offsets between antenna and RP for depth reference (WL at Transducer)

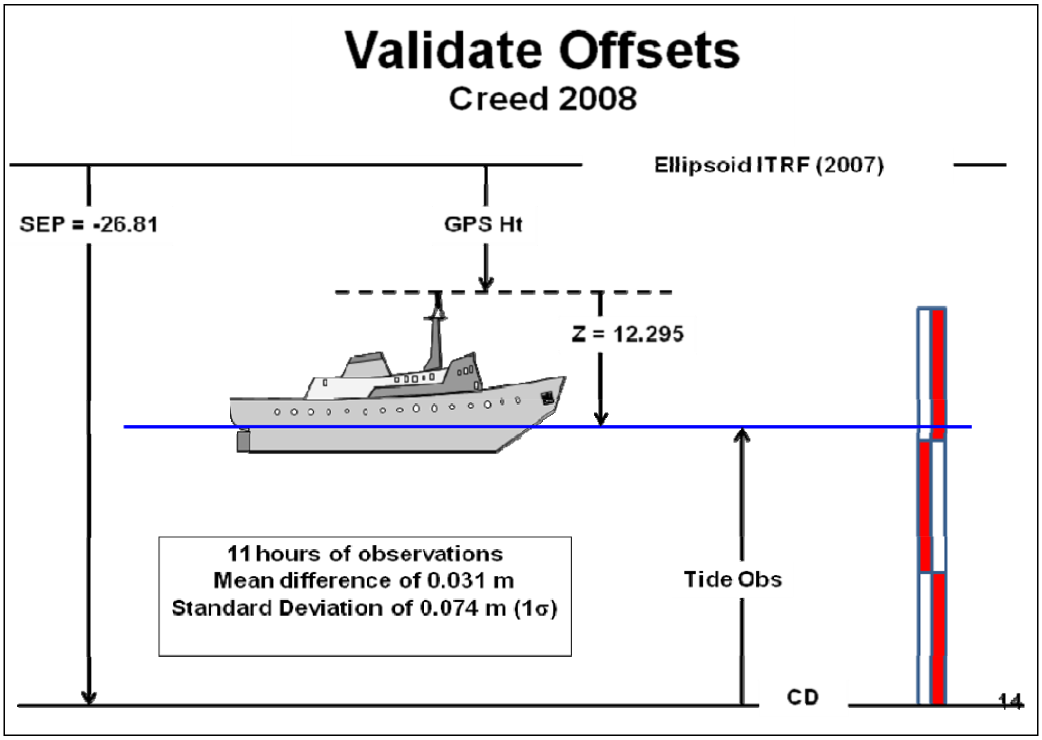

Figure 6: Creed 2008 Vertical Offset Diagram

3. Compare GPS WL to SJ Tide Gauge using Matlab routine (see Figure 7)

4. Create HIPS compatible text file
    - Concatenate all OMNIStar files for each survey using DOS “copy” command
    - Run through Matlab routine to extract Date, Time, Lat, Long, height (ITRF), standard deviation lat long ht

5. Import into HIPS, include GPS height uncertainty as SSS ht (SSS ht used as a place holder only)
6. Compute GPS tide (no vertical shift) and remerge.
7. Use the HIPS Attitude editor to verify time synchronization
8. Create a new surface and evaluate standard deviation surface for GPS tide errors (see Figure 8)
9. Evaluate areas of concern in the HIPS Attitude editor, viewing GPS heights, heave, GPS Tide and SSS ht (proxy for vertical standard deviation
10. Create final surface

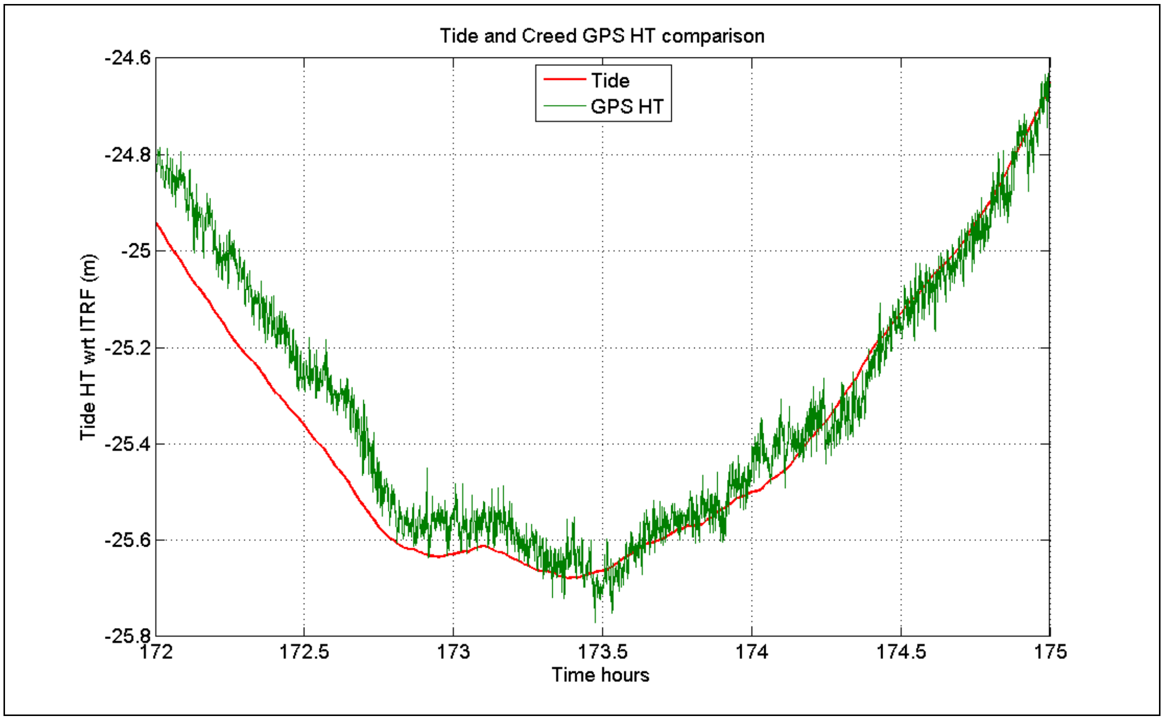

Figure 7: Creed and Saint John Gauge Comparison. Mean = 0.031 m, standard deviation = 0.074 m (1σ)

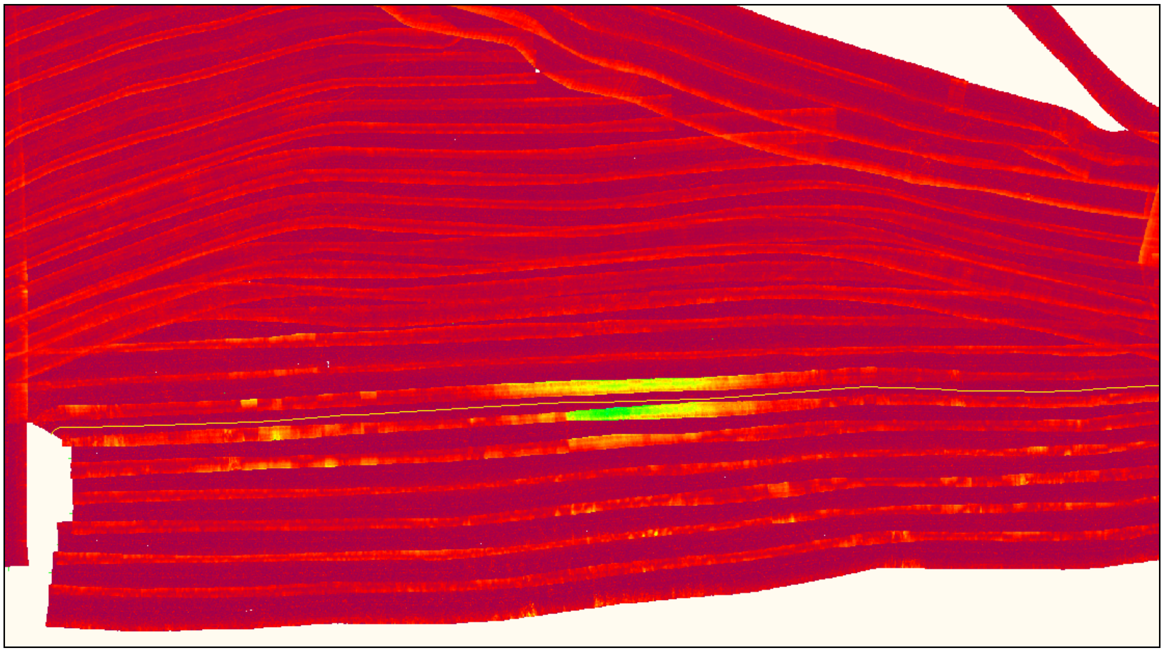

Figure 8: Sample standard deviation surface with GPS tide error

11. For data without GPS tides:
    - Create navigation files from survey lines for use in WebTide. WebTide generates a MSL water level value given a position and time.
    - Create standard HIPS tide files from WebTide MSL results
    - Remerge HIPS HDCS files using standard tides
    - Create new base surfaces

12. Using the CARIS Bathymetry Editor, compare 2007 through 2009 GPS tide surfaces (ITRF).
    - Find overlap between any of the surfaces and compute the surface difference.
    - Export an ASCII file of the difference surface
    - Using Matlab, compute the mean and standard deviation

13. Using the CARIS Bathymetry Editor, combine the 2007 through 2009 GPS tide surfaces (ITRF). Newer surveys to take precedence in overlap areas.

14. Using the CARIS Bathymetry Editor, transform the WebTide derived MSL surfaces (Creed 1996. 1999 and 2006) to the ellipsoid using CSRS NTv2 geoid to ellipsoid (ITRF97) model

15. Using the CARIS Bathymetry Editor, compare the shifted WebTide derived surfaces (Creed 1996. 1999 and 2006) to the combined 2007 through 2009 GPS tide generated surface. Evaluate the difference surface in Matlab.

16. Using the CARIS Bathymetry Editor, combine the shifted WebTide derived surfaces (Creed 1996. 1999 and 2006) with the 2007 through 2009 GPS tide generated surface.

17. Using CARIS Bathymetry Editor, translate the combined surface from ITRF97 to the geoid through CSRS NTv2.

5 Vessel Configuration

When processing and applying GPS heights in CARIS HIPS it is very important to ensure that the vessel configuration file (VCF) has the appropriate settings. If the high-accuracy GPS positions are to be imported with the GPS heights, then it is important to ensure that the VCF is configured for the appropriate position reference point. If the original navigation observations are to be used, then it is important to configure the VCF so that the appropriate horizontal reference is used, keeping in mind that the GPS height may have to be corrected for pitch and roll.

For most of the survey platforms used in the Bay of Fundy project, the GPS antenna was very either very close to the transducer, in the horizontal plane, or the GPS height was translated to the vessel reference point during data collection, as was the case with the Matthew. With small horizontal lever arms (less than 1 m), the effect of pitch and roll on the height translation was minimal. However, this was not the case for the Creed, where the fore/aft offset between the GPS antenna and transducer was over 7 metres. Another complication with the Creed data was that the heave observation included pitch and roll induced heave. These effects were removed from the heave (Apply MRU Remote Heave in the CARIS HIPS GPS Tide Computation), to get the actual heave at the RP. Pitch and roll were used to translate the GPS height from the antenna to the RP and then to the Transducer. The following is an example of how the Creed GPS heights were processed in CARIS HIPS (See Figure 10):

- Recorded heave was of the transducer, including pitch and roll induced heave.
- Positions (3D) were of the antenna.
- Offsets for the transducer were from the RP (MRU):
  - X (stbd)= 3.850
  - Y (fwd)= 5.380
  - Z (down)= 0.00 (Imported depths relative to the waterline)
- Offsets for the Antenna (from the RP):
  - X = 0.0
  - Y = -2.0
  - Z = -10.82
- Heave (**NOT applied in merge, for GPS Tide computations only! Will be used to remove pitch and roll induced heave).** Offsets were input assuming that the heave observations were at the transducer, therefore, the offsets were from the RP to the transducer
  - X = 3.85
  - Y = 5.38
  - Z = 4.24

- Offset for the waterline (**Do NOT apply in merge, for GPS Tide computations only!).** This is used to translate the GPS height from the RP to the waterline
    - WL = 1.25

The CARIS HIPS GPS Tide computations settings (using the ellipsoid as the datum) for this example are shown in Figure 9

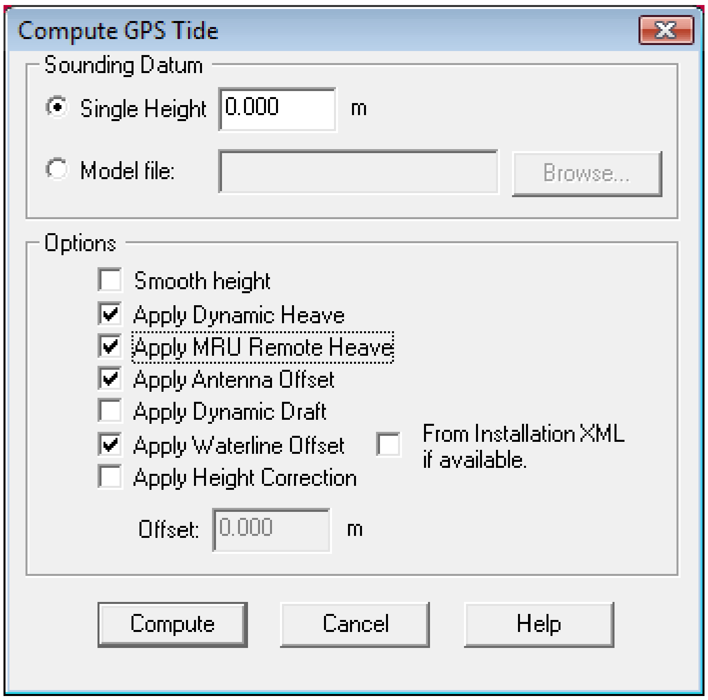

Figure 9: Compute GPS Tide for Creed example

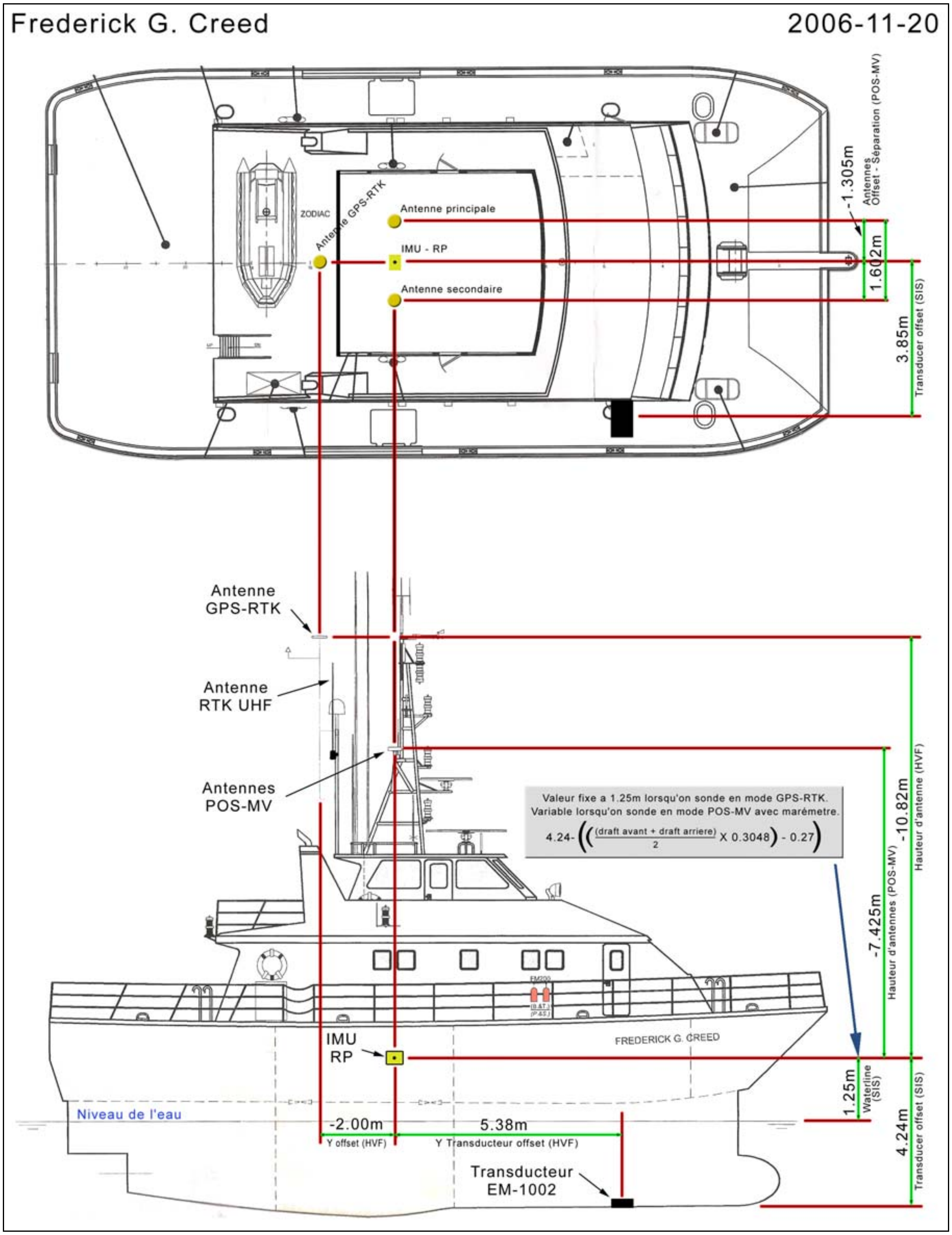

Figure 10: Creed Diagram

6 WebTide Evaluation

Data that did not have GPS heights were tidally corrected using Webtide and the Scotia Shelf model. These MSL referenced surfaces were then translated to the ITRF 97 ellipsoid using NTv2. In order to validate these processes two Webtide evaluations were performed. The first looked at a very small section in the North-east and the second looked at the entire area covered by GPS heights (2007, 2008 and 2009, Creed, Matthew, Plover and Pipit).

6.1 North East Evaluation

A small section of the 2009 survey was used to compare GPS tide and shifted WebTide surfaces. A standard deviation surface from the GPS Tide generated results is shown in Figure 11, and from the WebTide results is shown in Figure 12. Note the high standard in the line to line overlap areas of the WebTide surface. The difference between GPS Tide and shifted WebTide is shown in Figure 13. The striping shown in this figure clearly indicates the discrepancy between lines resulting from the WebTide model.

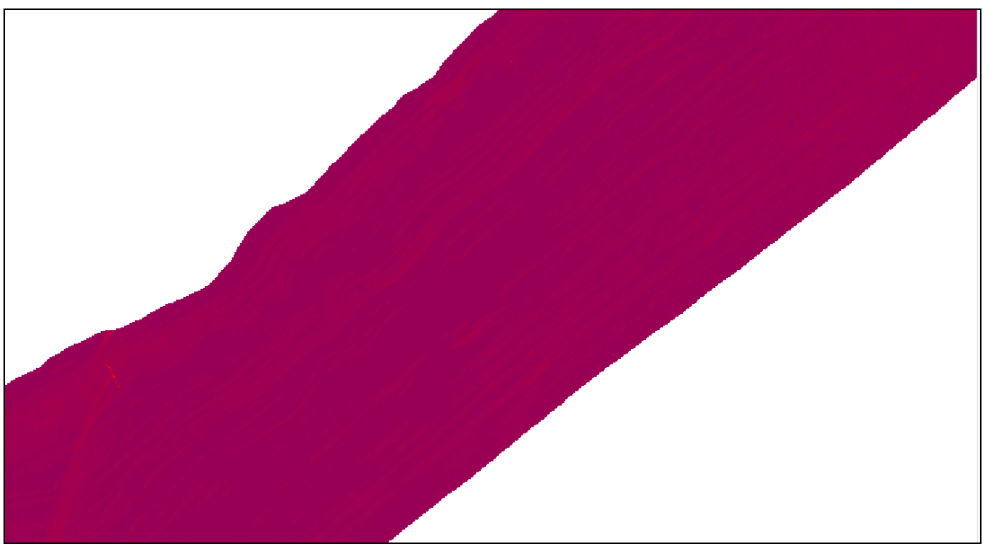

Figure 11: 2009 GPS Tide standard deviation surface.

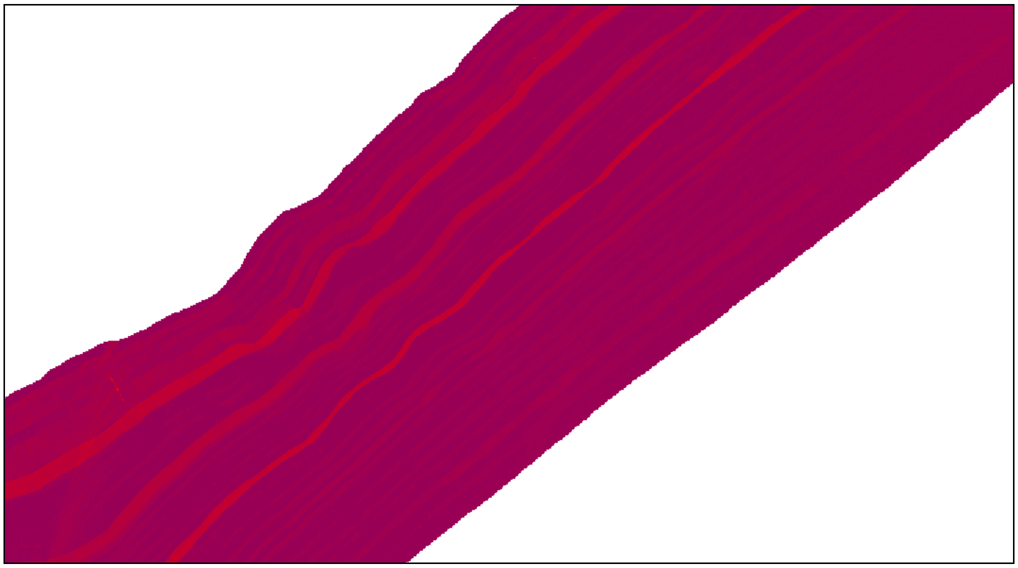

Figure 12: 2009 WebTide standard deviation surface.

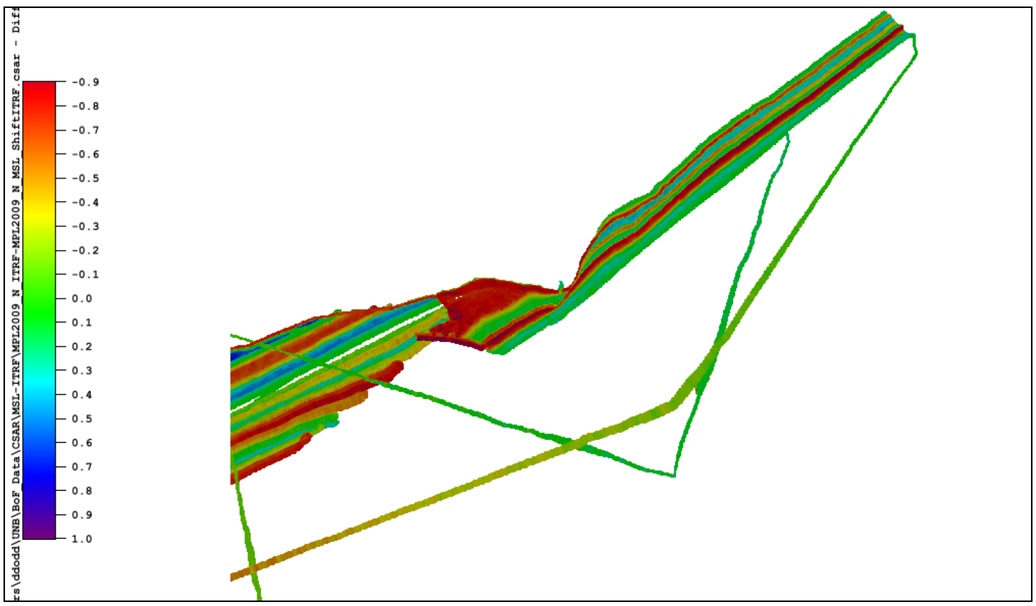

Figure 13: Difference between GPS Tide and shifted WebTide surfaces. Legend is ±1 m

Figure 14 shows a plot of the difference between GPS Tide and WebTide for the region shown in Figure 13. The mean is -0.125 m and the standard deviation is 0.40 m (1σ). The mean difference is due to the MSL to geoid separation (Sea Surface Topography), which is not accounted for here. The standard deviation is due primarily to the WebTide model phase and amplitude uncertainty. This would indicate that using the WebTide generated surfaces (with the Scotia Shelf model) introduces a significant variation in the bottom, but overall, this variation averages out. This indicates that the MSL model is consistent with the geoid surface generated from CSRS NTv2.

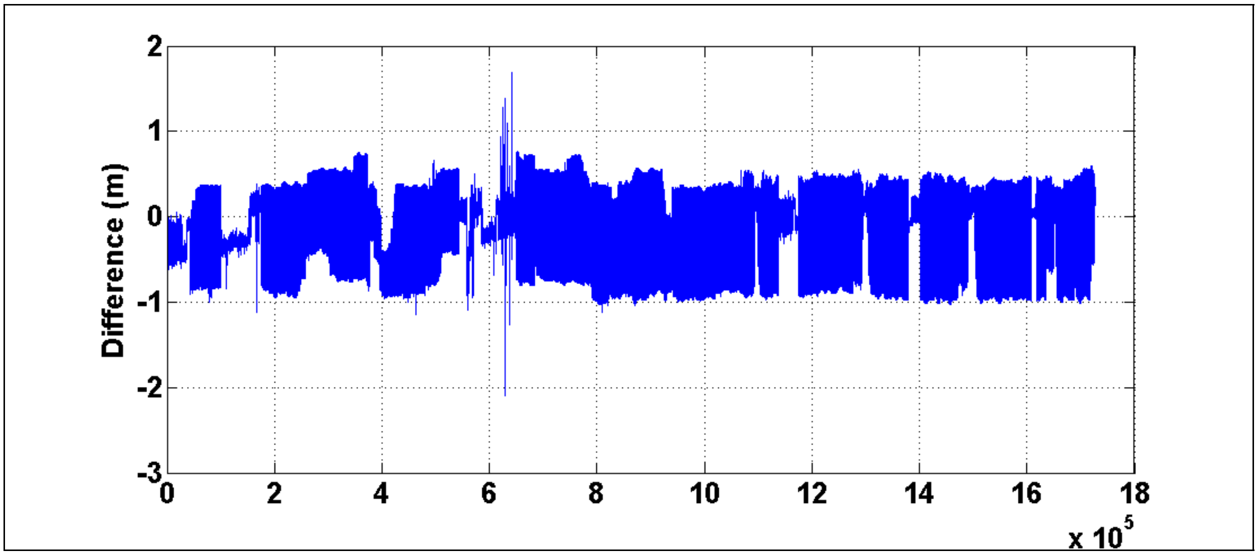

Figure 14: Plot of difference between GPS Tide and WebTide for section of 2009 survey. Mean = -0.125, Standard deviation = 0.400

6.2 Map Sheet Evaluations

All of the data with GPS heights (Creed, Matthew, Plover and Pipit from 2007, 2008, 2009) was processed with WebTide correctors. The resulting two surfaces were differenced (GPS Tide – WebTide) and then evaluated. Means and standard deviations (1σ) were determined for each of 17 map sheet (see Table 1 and Figure 15). For all but map sheet 14, the mean difference was negative, indicating that the Webtide derived surface was lower that the GPS tides derived surface.

The translation from the Webtide derived MSL surface to ITRF was performed using the NTv2 model, which translated from the Geoid03 to ITRF(97), not taking into consideration sea surface topography (separation between MSL and the geoid). The resulting differences (shown in Figure 15) indicate a large negative SST region along the south-east area of the Bay. It indicates a region of lower SST around Grand Manan and into Passamaquody Bay. Given the relatively high standard deviations (16 cm to 53 cm), it would not be prudent to read too much into these results. The standard deviations show the consequence of using a prediction model to remove the effect of tide in the Bay of Fundy.

Map Sheet	Mean	Standard Deviation
1	-0.164	0.156
2	-0.243	0.224
3	-0.301	0.224
4	-0.024	0.526
5	-0.360	0.209
6	-0.260	0.235
7	-0.035	0.278
8	-0.287	0.206
9	-0.241	0.239
10	-0.069	0.235
11	-0.166	0.260
12	-0.083	0.305
13	-0.311	0.328
14	0.033	0.261
15	-0.080	0.281
16	-0.201	0.465
17	-0.139	0.382

Table 1: Webtide and GPS Tide difference means (m) and standard deviations (m)

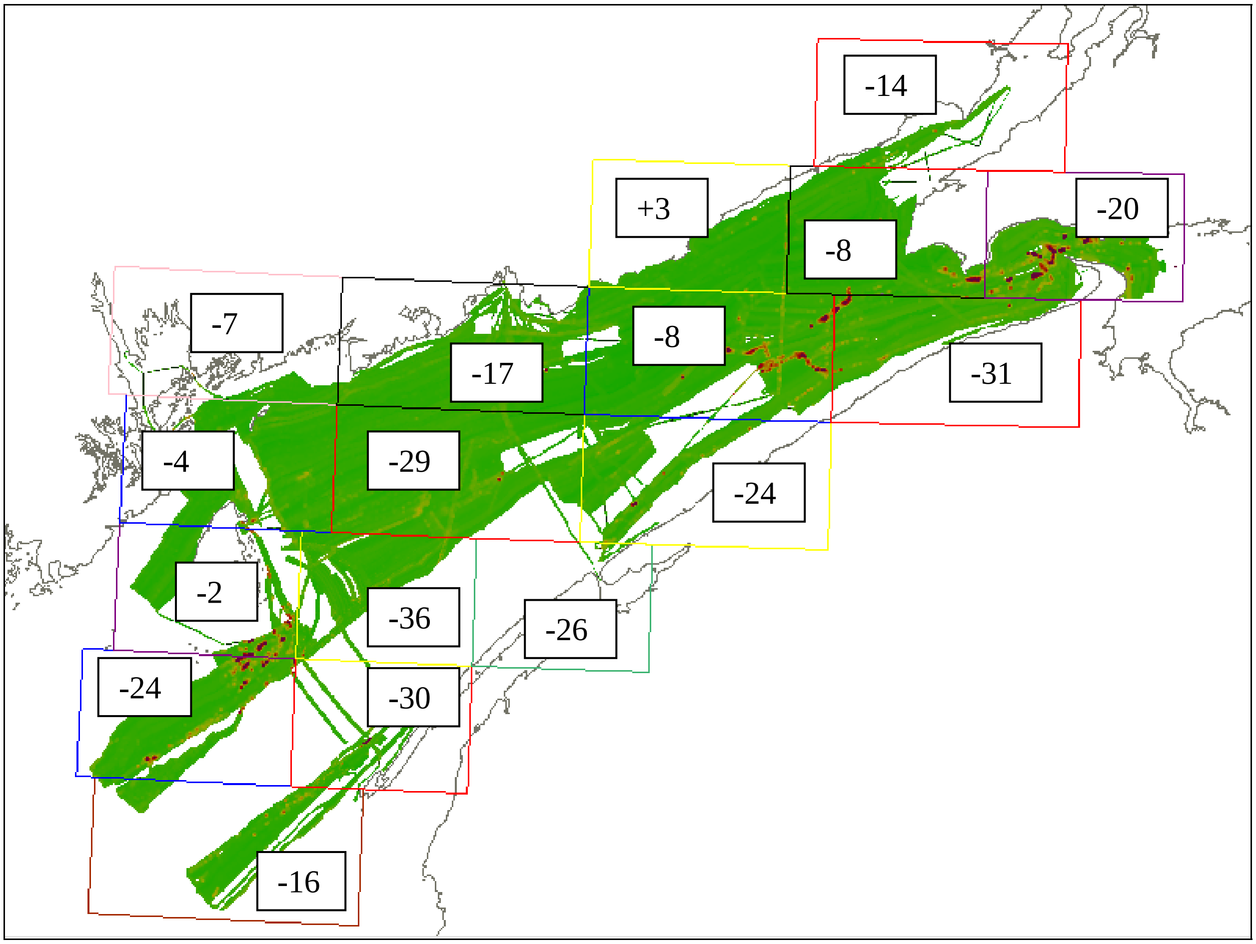

Figure 15: Map Sheet and difference means (in cm)

7 Results

For the most part, the tide gauge evaluation results were good. Unfortunately, not all vessels for all years had GPS height data from Saint John. Inter-comparison between the Creed, Matthew, Plover and Pipit surveys of 2007 through 2009 were used as the ultimate vertical offset check. Mean offsets varied from a low of 0.02 metres to a high of 0.25 metres, indicating a very close comparison between surveys. The standard deviations (all at 1σ), from the 2008 and 2009 surveys varied from 0.1 m to 0.2 m. The standard deviations from the 2007 surveys varied from 0.5 m to 1.0 m. This high standard deviation can be attributed to problems with the high-accuracy GPS solutions and possible changes in the bottom.

More diligent editing of the GPS heights is required to reduce the standard deviations from the 2007 surveys and improve the confidence in the resulting surfaces. However, the only way to edit bad GPS is to remove the affected depths from the dataset, which creates holes (data holidays) in the resulting surface. A solution to this is to use the shifted WebTide generated surfaces for the data holidays. Differencing good GPS tide surfaces from the shifted Webtide surfaces for the same area and time will provide any necessary bias shifts. Due to time constraints, this process was not conducted for this project. Although the majority of the artefacts due to bad GPS heights were removed, some remained in the final surface.

The depth data received in CARIS HDCS format from CHS Atlantic was already cleaned. Data imported into CARIS from raw telegram files had to be cleaned before final surface generation. This was the case for the 1996 and 2006 Creed surveys. Data were cleaned by removing obvious outliers, and in the case of the 1996 data set, some sound velocity refraction editing was necessary.

7.1 Creed 1996

The Creed 1996 survey was edited for outliers and sound velocity errors. A MSL surface was generated using WebTide for tidal corrections. The resulting surface was translated to the ITRF ellipsoid and then differenced from the 2007 through 2009 combined ITRF surface (see Figure 16). The mean difference was 0.15 m with a standard deviation of 0.57 m.

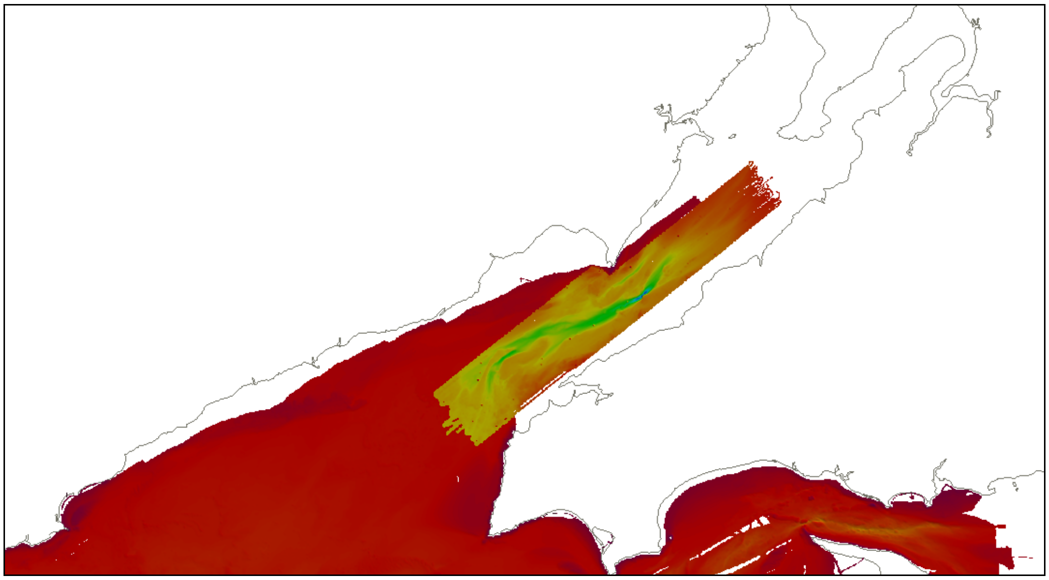

Figure 16: Creed 1996 survey on top of the 2007 through 2009 combined surface

7.2 Creed 2006

The Creed 2006 survey was edited for outliers. A MSL surface was generated using WebTide for tidal corrections. The resulting surface was translated to the ITRF ellipsoid and then differenced from the 2007 through 2009 combined ITRF surface (see Figure 16). The mean difference was -0.45 m with a standard deviation of 0.60 m.

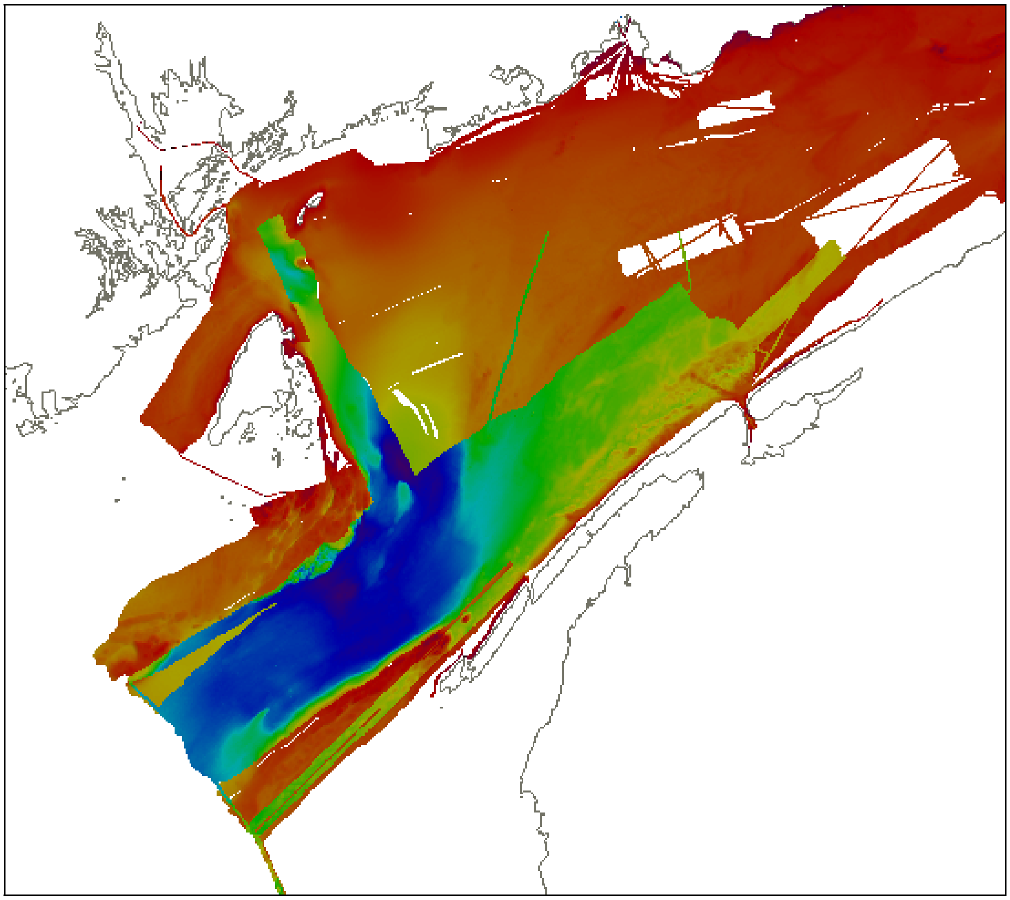

Figure 17: Creed 2006 Survey on top of the 2007 through 2009 combined surface

7.3 Creed 1999

The Creed 1999 data set was handled slightly differently than the Creed 2006 and Creed 1996. CARIS HDCS files were provided for this data set that included tide files. These chart datum referenced tide files were used rather than generating new predicted tides using MSL referenced WebTide. A chart datum surface was created from the data set, which was then translated to an ITRF reference, which included the MSL/Chart datum offset. This surface was then differenced from the combined 2007 through 2009 ITRF surface. The difference surface was divided into 7 areas for individual evaluation (see Figure 18). The resulting statistics are shown in Table 2. Only three areas were used for integration into the larger data set; North, Centre and East. Each area was shifted by the bias, assumed to be the chart datum/geoid separation. The resulting surfaces were merged into the existing ITRF surface.

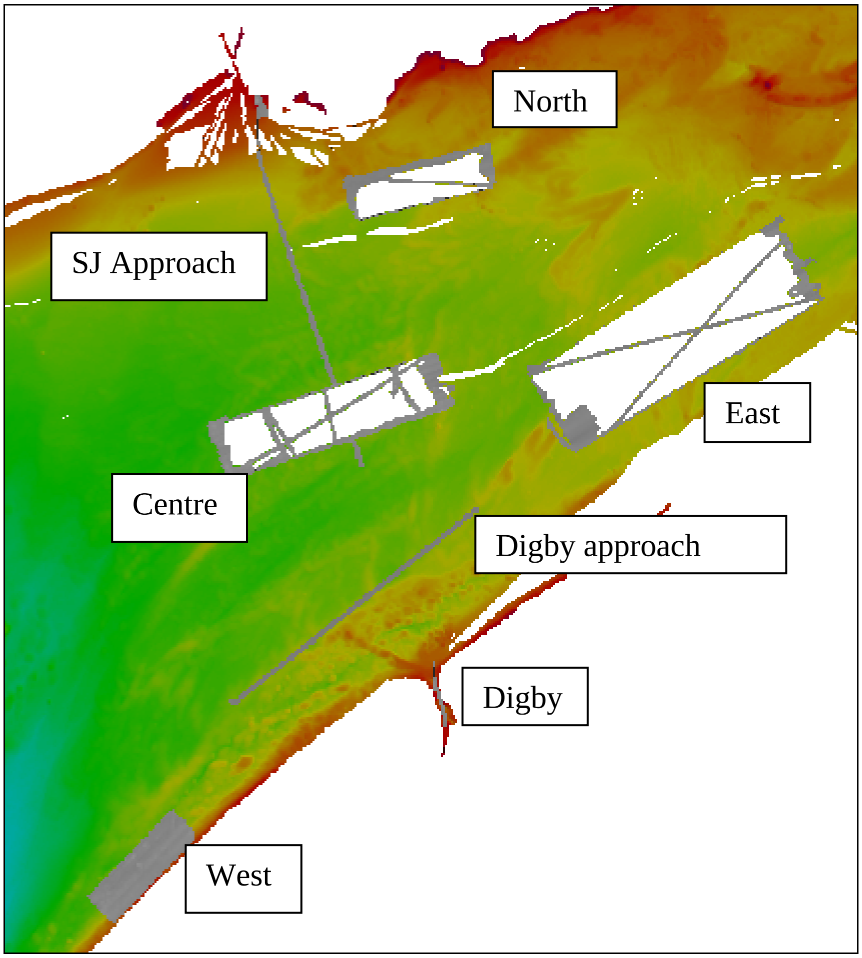

Figure 18: Creed 1999 Difference Evaluation Areas

Area	**Mean**	**St Dev**
Centre	4.222	1.041
Digby	6.220	1.108
Digby Approach	7.074	0.470
East	5.124	1.655
North	5.284	1.083
SJ Approach	5.172	0.731
West	4.965	1.142

Table 2: Combined ITRF - Creed 1999 statistics

7.4 Heron 2006, 2007 and 2008

Several data sets collected by the UNB OMG using the Heron in 2006, 2007 and 2008 were incorporated into the final surface. These data sets were imported and cleaned in HIPS, where WebTide derived tidal correctors were used to remove the tidal effect. The resulting surfaces were translated to ITRF and merged with the other data sets.

Some areas of Passamaquoody Bay were still missing. These data were supplied by the UNB OMG in the form of 5 m XYZ grid text files. These files were translated to ITRF and then incorporated into the overall dataset.

7.5 Final Surface

Figure 19 shows the final combined surface. This is a 6 GB 5X5 m surface in CARIS CSAR format (All_CMPPLH_96thru09_ITRF_Inter_UNB.CSAR). This surface can be viewed using the freeware program CARIS Easy View. The surface is comprised of data from the Creed, Mathew, Plover, Pipit, and Heron collected from 1996 through 2009.

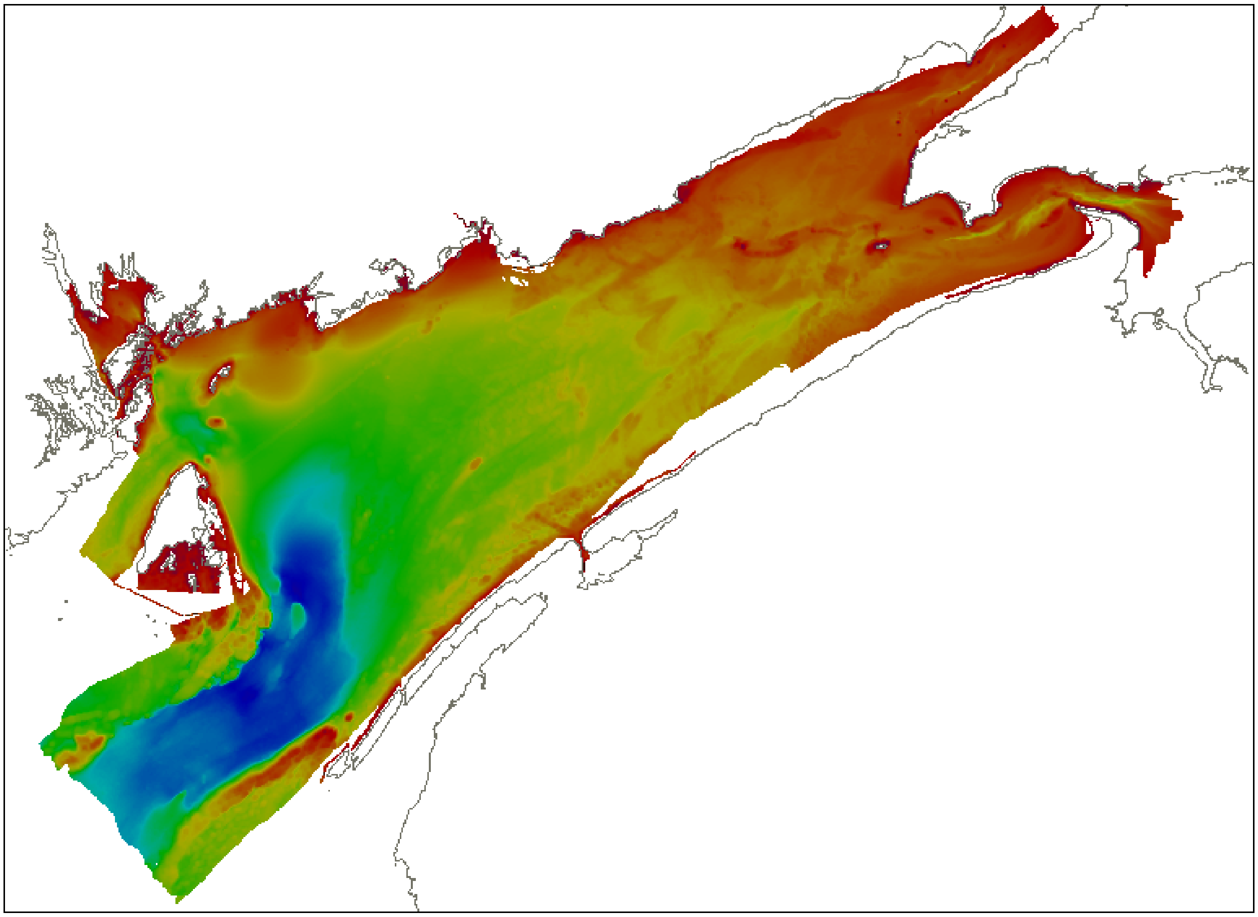

Figure 19: Final Bay of Fundy surface (ITRF)

8 Deliverables

The final deliverable was in the form of Easting, Northing and Depth text files. One file was created for each of 17 map sheet (see Figure 20). Map sheet boundaries were provided by Geological Survey of Canada (GSC) Atlantic. Horizontal coordinates were in UTM Z20 (NAD 83). The vertical positions were relative to the geoid (~MSL), derived from the CSRS NTv2 ITRF (97) to Geoid03 translation, positive up. Files were uploaded to the UNB OMG website for retrieval by GSC.

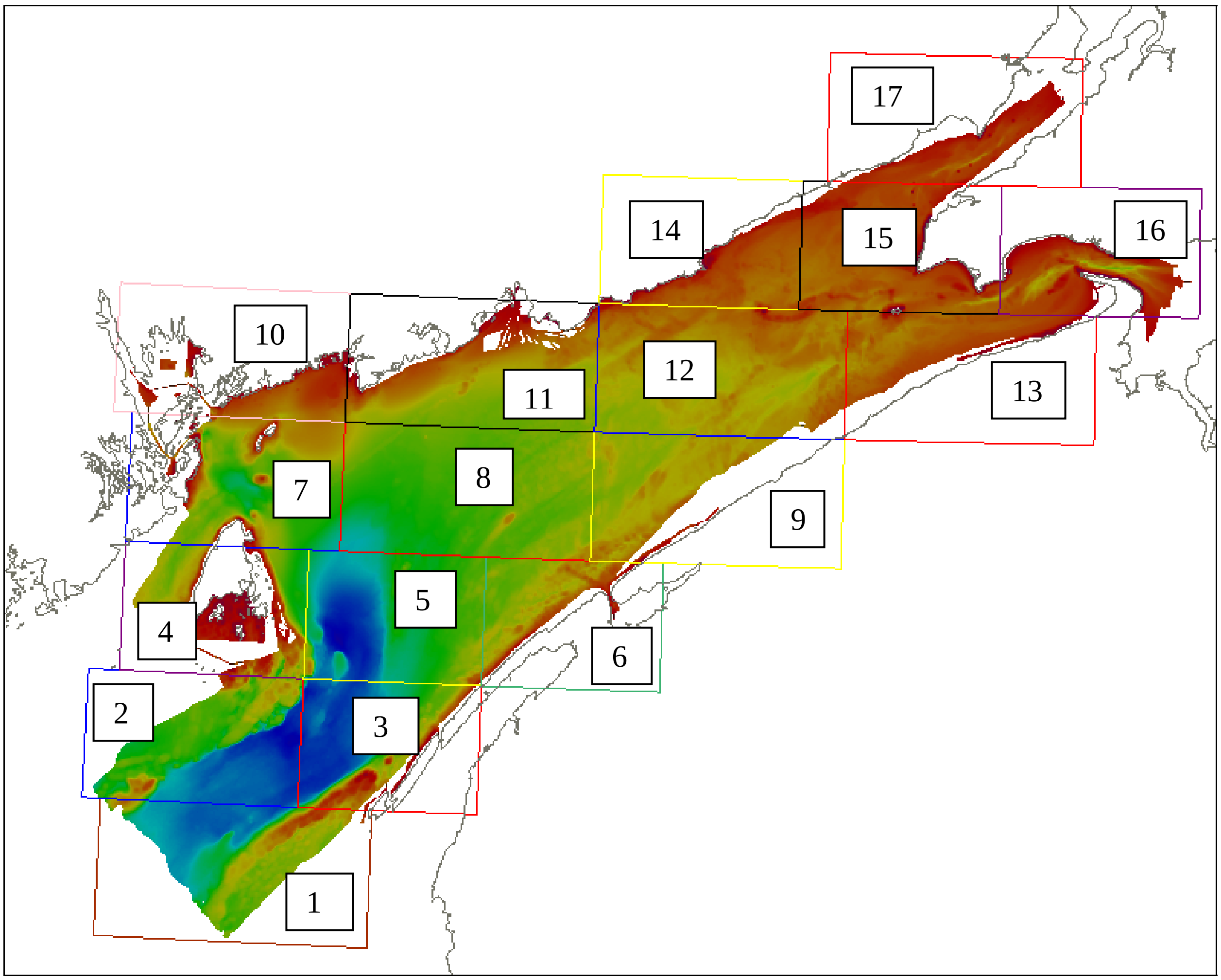

Figure 20: Map Sheet Boundaries

9 Conclusions and Recommendations

On average, the predicted tide surfaces agreed well with the GPS tide generated surfaces, even though large discrepancies occurred. The mean differences could be attributed to Sea Surface Topography; however, this must be investigated further before any definitive conclusions can be drawn. The standard deviation of the differences indicated the effect of using a hydrodynamic model that does not capture the true nature of the Bay of Fundy tides. A closer evaluation of these differences could be used to help improve the models, and a re-evaluation conducted to validate those improvements.

Further cleaning of GPS data is required in order to remove all GPS height related artefacts. In areas where GPS heights have been removed, locally shifted predicted MSL tides (WebTide) were used, but not all anomalies were detected and removed.

Using GPS heights to remove all vertical vessel movement from the data is a very effective method for producing consistent bathymetry. The challenge is in developing the models for translating that GPS derived surface to a chart datum.

For future surveys it is recommended that raw GPS data be recorded constantly on all survey platforms. As an integral part of the calibration process prior to the beginning of a project, vessel should spend some time by a tide gauge where the separation between the ellipsoid and chart datum are well established. Theses calibration data sets should be considered a vital component of the overall data and be stored with the production survey files.

The surfaces produced for this project were at 5 m resolution. This was chosen to avoid gaps in the data in deeper water. A much more desirable solution would be to have a multi-resolution surface, where it could be reduced to 1 m or less near shore and expand to 5 m or greater in the deeper waters, depending on depth observation spacing and feature form. Research is being conducted in the development of these surfaces.